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TRANSMISSION EFFECTS ON PLASTIC FILMS IRRADIATED WITH ULTRAVIOLET LIGHT, ELECTRONS, AND PROTONS

by Evelyn Anagnostou and Adolph E. Spakowski

Lewis Research Center
Cleveland, Ohio

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16. Abstract

Several plastic films, suitable as covers for thin-film CdS solar cells, were irradiated by ultraviolet light in vacuum. The films were bombarded by 1-MeV electrons at fluences up to 1×10^{17} electrons/cm^2, and one of the films was bombarded by 800-keV protons at fluences up to 1×10^{14} protons/cm^2. The effect of these environments on the transmission of the plastics in the wavelength range 0.350 to 1.200 μm was measured. The most promising cover material was Teflon-FEP.

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SUMMARY

Thin-film cadmium sulfide solar cells require a cover plastic for use in space. Several plastic films including Kapton, which is presently in use, were irradiated by ultraviolet light in vacuum. The intensity of the source was equivalent to 7.5 suns for wavelengths of less than 0.300 micrometer. The maximum irradiation time was 20 300 equivalent solar hours. All the films were bombarded by 1-MeV electrons at fluences up to 1×10^{17} electrons per square centimeter. One of the films, Teflon-FEP, was irradiated by 800-keV protons at fluences up to 1×10^{14} protons per square centimeter. The transmission of the films in the wavelength range 0.350 to 1.200 micrometers was monitored. The Teflon-FEP performed very well under all conditions, and its superior transmission in the wavelength range of interest makes it a good candidate as a solar cell cover. Kapton decreased in transmission by 13 percent under the conditions of the ultraviolet test. Parylene, Mylar-WD (weather durable), X101, and PPT films all degraded under the test conditions.

INTRODUCTION

Thin-film cadmium sulfide solar cells are produced for various Earth and space applications. For space use, the cells have Kapton (H-film) plastic covers. In this configuration and under the conditions of solar flux at air mass zero and an operating temperature of 60° C (near-Earth orbit conditions), these cells have efficiencies near 3 percent. In principle, increases in cell efficiency can be achieved by the use of a cover plastic that allows more solar radiation in the useful wavelength range, 0.400 to 1.200 micrometers, to reach the cell. Although the present cover plastic, Kapton, absorbs a considerable amount of visible light, it is stable to the environmental conditions found in space. Therefore, not only must the alternative cover plastic be ini-

tially more transparent than Kapton, but it must also be able to withstand the ultraviolet, electron, and proton radiation it will encounter in space without serious degradation in transmission.

Screening tests of possible cover plastics made at the NASA Lewis Research Center (ref. 1) indicated that Kapton and weather-durable Mylar were the best, with Kapton the more stable of the two in the radiation environment. Recently, promising new materials have become available. Several of these materials together with Kapton and Mylar have been subjected to irradiation by ultraviolet light and several levels of electron and proton bombardment. Results are reported herein on the following films: (1) Mylar-R (regular), (2) Mylar-WD (weather-durable), (3) X101, an experimental polymer, (4) PPT, poly (phenylene) triazole, (5) Kapton, a polyimide, (6) Parylene, poly (p-xylylene), (7) Polysulfone, a Bakelite resin, and (8) Teflon-FEP, a completely fluorinated ethylene-propylene copolymer.

The plastic films were irradiated in a vacuum of 10^{-6} torr. The light source consisted of 10 high-pressure mercury arc lamps that produced a light intensity of 7.5 suns for wavelengths less than 0.300 micrometer. An additional low-pressure mercury arc lamp was used for some of the tests; it provides light at 0.185 micrometer but did not add significantly to the overall intensity. Films were irradiated up to 20 350 equivalent solar hours (ESH). The unit, equivalent solar hour, is simply the product of actual time and the number of "suns" for the radiation range in question. In this report, ESH represents irradiation by wavelengths less than 0.300 micrometer. The transmission spectra in the wavelength range of 0.35 to 0.75 micrometer were recorded before, during, and at the completion of the tests. The transmission to the usable solar radiation was then determined and compared.

A Cockcroft-Walton accelerator was used to conduct electron bombardment tests on X101, PPT, Kapton, and Mylar-WD. The tests were conducted in air at atmospheric pressure by using 1-MeV electrons at fluences of 10^{15} to 10^{17} electrons per square centimeter. Electron bombardment tests were also conducted on Teflon-FEP in the Van de Graaff facility at the NASA Goddard Space Flight Center. These tests were conducted in vacuum using 1-MeV electrons at fluences of 10^{15} to 2×10^{16} electrons per square centimeter. This plastic was then subjected to 800-keV protons at fluences of 10^{12} to 10^{14} protons per square centimeter in the same facility. (Julius Hirschfeld of NASA Goddard Space Flight Center performed the proton and electron irradiation of Teflon-FEP.)

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The equipment used for the ultraviolet irradiation of the plastics is similar to that used in reference 1. Small samples of plastic film were held in contact with a metal

water-cooled plate either by clips or with glass microscope slides across the ends. In the vacuum chamber, the average pressure during the irradiation was $2\pm1\times10^{-6}$ torr. The temperature of the plate, measured by an attached iron-constantan thermocouple, was $33^{\circ}\pm2^{\circ}$ C.

The plastic films were irradiated through a 1-inch (2.54-cm) quartz plate window by ten 100-watt high-pressure mercury vapor lamps, Hanovia type SH, placed 7.9 inches (20 cm) from the samples. For some of the tests, an additional 2-watt low-pressure mercury lamp was included as part of the light source. This lamp has 2 percent of its output at 0.185 micrometer and 86 percent at 0.254 micrometer. The lamp was enclosed in the vacuum chamber by means of a quartz tube sealed at the chamber walls and flushed with dry nitrogen gas to prevent oxygen absorption of the light. Measurements of the light intensity below 0.300 micrometer were made using a water-cooled Eppley eight-junction lampblack-coated bismuth-silver thermopile, with and without a pyrex glass filter, opaque below 0.285 micrometer. The thermopile has a manufacturer's limit of error of ±2.0 percent and a maximum calibration error of ±2.0 percent. Voltages were measured with a digital voltmeter. The filtered intensity was subtracted from the total intensity with a correction made for the heating of the thermopile. This correction introduces an uncertainty of ±8.0 percent. A correction must also be made for the absorption of the filter. This technique yields a value of 7.5±0.7 suns at 1 astronomical unit for wavelengths less than 0.300 micrometer. No intensity difference could be measured when the 2-watt lamp was included. The light intensity at other wavelengths was not measured since it is only light of wavelengths less than 0.300 micrometer that has sufficient energy to disrupt bonds in plastics and thereby produce damage (ref. 2).

Figure 1 compares the radiated energy of the lamps to the solar energy extrapolated from Johnson's data (ref. 2) with respect to wavelength. The energy distribution of the solar spectrum below 0.220 micrometer is shown as a smooth curve, although the energy distribution in this range is a combination of continua and line sources. The figures for the mercury lamps were taken from data supplied by the manufacturer. This figure is meant to give a qualitative comparison only.

The electron irradiations at Lewis were performed with a Cockcroft-Walton accelerator. The samples were irradiated in air at atmospheric pressure and were cooled by a blower to approximately 25° C. The energy of the electrons can be determined to better than ±10 percent. The dose rates were measured using the Faraday cup method, which gives values good to ±10 percent.

The electron and proton irradiations at the NASA Goddard Space Flight Center were performed with a high-voltage Van de Graaff accelerator. The samples were irradiated in vacuum and were water cooled. The energy of the particles and dose rates can each be determined to ±10 percent.

The transmission of the films was measured with a Perkin-Elmer 350 spectro-

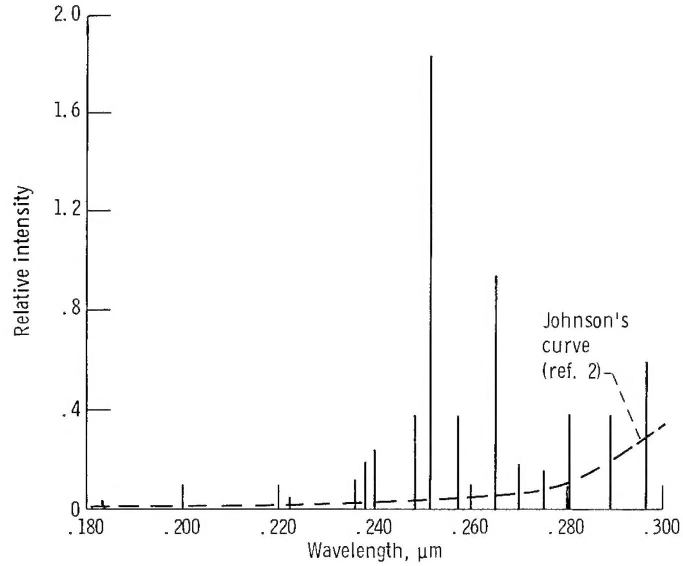

Figure 1. - Qualitative comparison of spectral lines in light source with Johnson's curve for wavelengths less than 0.300 micrometer. Data for both high- and low-pressure mercury arc lamps included.

TABLE I. - COMPOSITION AND SOURCE OF PLASTICS USED IN STUDY

Plastic film	Composition	Manufacturer
Mylar-R (regular)	Polyethylene terephalate	DuPont
Mylar-WD (weather durable)	Polyethylene terephalate and a proprietary ultraviolet screening agent	DuPont
X101	Experimental, proprietary	Monsanto
PPT	Poly (phenylene) triazole	Monsanto
Kapton	Polyimide	DuPont
Parylene	Poly (p-xylylene)	Union Carbide
Polysulfone	Bakelite resin	Union Carbide
Teflon-FEP	Completely fluorinated ethylene-propylene copolymer	DuPont

photometer. Initially, measurements were made in the wavelength range 0.350 to 1.200 micrometers. Later, only the transmission in the range 0.350 to 0.750 micrometer was measured because the transmission of the films beyond 0.750 micrometer could be extrapolated with sufficient accuracy. The total reflectance for cells covered with Mylar-R, Kapton, and Teflon-FEP was measured in the wavelength range 0.400 to 1.200 micrometers by using an integrating sphere technique. The reflectance for Mylar-R- and Kapton-covered cells was determined with a Perkin-Elmer 350 spectrophotometer and that for the Teflon-FEP-covered cell with a Gier-Dunkel reflectrometer. These measurements are reproducible to ±5 percent. The plastics studied are listed in table I. All of the films are 1 mil (25 μm) thick.

RESULTS AND DISCUSSION

The transmissions of the different plastic films were compared by treating the data in the following way. Light radiation in the range of 0.350 to 1.200 micrometers was arbitrarily divided into several continuous wavelength bands. The amount of solar energy at 1 astronomical unit and air mass zero in each band was obtained from Johnson's curve (ref. 2) and was multiplied by the average transmission of the plastic in the same wavelength interval, which yielded the amount of solar energy transmitted. These energies were summed over the response range of the cell and compared to that obtained for Mylar-R at time zero computed in the same way. Thus, all values are reported as percentages of the transmission of 1-mil (25 μm) Mylar-R, which, through the range 0.350 to 1.200 micrometers, transmits 87 percent of the solar energy available.

The transmission measurements are reproducible to ±2.2 percent. The spectrophotometer has a reproducibility of ±0.5 percent, and the method of calculation of the overall transmission will introduce a maximum error of ±1.0 percent. The largest error results from the variability in the plastics themselves. For example, Kapton is produced without color control (private communication from H. Hite, E. I. DuPont de Nemours and Co., Wilmington, Del.) and the transmission of Kapton samples ranged from 74 to 77 percent.

Ultraviolet Tests

The transmissions of Mylar-R, Mylar-WD, Kapton, and X101 are compared in table II. These data were obtained with an irradiation source that did not include the low-pressure mercury lamp. Two samples of X101 are listed. Sample 1, the first film supplied by the manufacturer, was not uniform in appearance and was slightly colored.

TABLE II. - EFFECT OF ULTRAVIOLET RADIATION ON TRANSMISSION OF MYLAR-R, MYLAR-WD, KAPTON, AND X101

[Source consisted of 10 high-pressure mercury arc lamps.]

Plastic	Ultraviolet radiation, ESH[a]								
	0	[b]1000	[b]2030	2140	2500	3510	5010	7650	9200
	Relative transmission[c], percent								
Mylar-R	100	83	--	79	--	--	--	--	--
Mylar-WD	98	--	89	--	--	87	--	--	--
Kapton	76	--	76	76	--	75	--	--	--
X101 (sample 1)	91	--	--	--	77	--	72	69	67
X101 (sample 1) irradiated[d]	85	--	--	--	78	--	71	70	67
X101 (sample 2)	97	--	--	83	83	--	--	--	--

[a]Equivalent solar hr for wavelengths less than 0.300 μm at 1 AU and AMO.
[b]Ref. 1.
[c]Transmission is calculated over wavelength range 0.350 to 1.200 μm and is expressed as percentage of initial transmission of Mylar-R.
[d]Irradiated with 8×10^{15} electrons/cm^2, 1-MeV electrons prior to ultraviolet irradiation.

Sample 2, supplied later, was uniform in appearance and clear. These results indicated that Mylar-WD had a higher transmission than the other films irradiated for the same or shorter times. Kapton was the least affected by the irradiation. Both samples of X101 darkened and appeared to be poorer in resistance to ultraviolet than Kapton. Included in table II are data for a sample of X101 irradiated by 8×10^{15} electrons per square centimeter (1-MeV electrons) and then subsequently irradiated by ultraviolet light. This film darkened initially from the electron bombardment but under ultraviolet light did not darken more than the unirradiated sample. This result may be attributed to annealing of the electron damage either before or during the ultraviolet test. The electron bombardment was performed in air, which is likely to affect the reaction which occurs. Also, it has been shown (ref. 3) that unless the damage is severe, it can be annealed out.

Inclusion of the low-pressure mercury arc as part of the light source modified the aforementioned results, as shown in table III and figure 2. The films irradiated were Kapton, PPT, Parylene, Mylar WD, Polysulfone, X101 (sample 2), and Teflon-FEP. Comparing the percent transmission from table III with that from table II for Mylar WD, Kapton, and X101 shows that a very small amount of more energetic radiation can do considerably more damage to the plastic. Mylar-WD and X101 deteriorated rapidly; after approximately 2000 ESH, they became darker than Kapton. Again, Kapton darkened

TABLE III. - COMPARISON OF TRANSMISSION OF PLASTIC FILMS IRRADIATED WITH ULTRAVIOLET LIGHT

[Source consisted of 10 high-pressure mercury arc lamps and one low-intensity, low-pressure mercury arc.]

Plastic	Ultraviolet radiation, ESH[a]							
	0	848	2070	3638	5895	7845	12 833	20 350
	Relative transmission[b], percent							
Kapton	75	74	74	71	70	69	67	65
PPT	94	81	76	69	65	64	---	---
Parylene	98	82	81	76	75	73	70	70
Mylar-WD	95	78	73	67	63	---	---	---
Polysulfone	99	73	70	67	64	54	---	---
X101 (sample 2)	97	79	73	68	64	63	---	---
Teflon-FEP	109	--	106	106	106	106	105	[c]104

[a]Equivalent solar hr for wavelengths less than 0.300 μm.
[b]All transmission data are expressed as percentage of initial transmission of regular Mylar (Mylar-R).
[c]16 210 ESH.

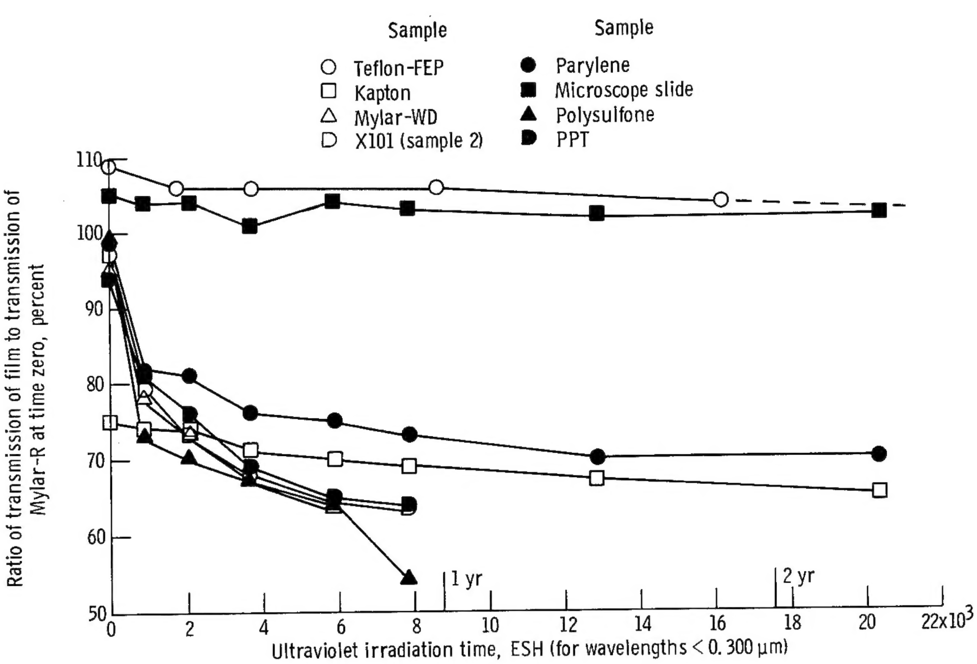

Figure 2. - Effect of ultraviolet irradiation on plastic films in vacuum. Radiation source, 10 high-pressure mercury arcs and one low-pressure mercury arc.

but more rapidly than under the previous conditions. PPT and Polysulfone did not perform as well as Kapton. Parylene, initially much more transparent than Kapton, darkened more quickly but always remained slightly more transparent. By far, the best performance was obtained from Teflon-FEP, which, after more than 16 000 ESH, had lost less than 5 percent of its transmission in the wavelength range of interest.

Figure 2 includes measurements made on a microscope slide used to hold down the films during the irradiations. The transmission on this slide was measured as a control to determine whether perhaps some of the darkening observed was the result of the deposition and subsequent polymerization of volatile materials in the system. The slide did darken over the course of the tests. This loss in transmission (less than 3 percent) represents the maximum loss that could be attributed to a film produced in the chamber since glasses themselves are darkened by ultraviolet light (ref. 4). The extent of darkening depends on the glass and the wavelength of the light.

Qualitatively, Kapton, Teflon-FEP, and Parylene did not become difficult to handle; that is, they retained flexibility. The other films became brittle and broke apart unless carefully handled.

In cadmium sulfide solar cells, the replacement of Mylar-R by Kapton as a cover plastic decreases the maximum power produced by the cell to 80 percent of its former value (ref. 5). A comparison of the transmission of solar energy of the films reveals that the transmission of Kapton is only 75 percent that of Mylar-R. Several factors could account for this difference. One is that the transmission values do not include the effect of the spectral response of the cell. The transmission was computed for the wavelength range over which the cells respond, but the variation of response within this range was not included. Another factor is that cadmium sulfide cells contain additional optical layers, such as adhesives, that contribute to differences in the reflectance of the cell packages. Figure 3 shows that the Teflon-FEP-covered cell has a reflectance closer to that of a Kapton-covered cell than that of a Mylar-R-covered cell. The low reflectance together with the higher transmission of Teflon-FEP may be expected to result in solar cells with efficiencies higher than those obtained with Mylar-covered cells.

The ultraviolet irradiation tests discussed herein point out several factors that must be kept in mind when data are extrapolated from laboratory experiments to outer space conditions. First, the spectral distribution of the light source is very important. The total solar spectrum in the ultraviolet region and below cannot be duplicated successfully on Earth, but narrow regions of the solar spectrum can be approximated. Second, just increasing the source intensity may not be equivalent to increasing irradiation time. How successfully these tests simulate space conditions will be determined only when space test data are actually available.

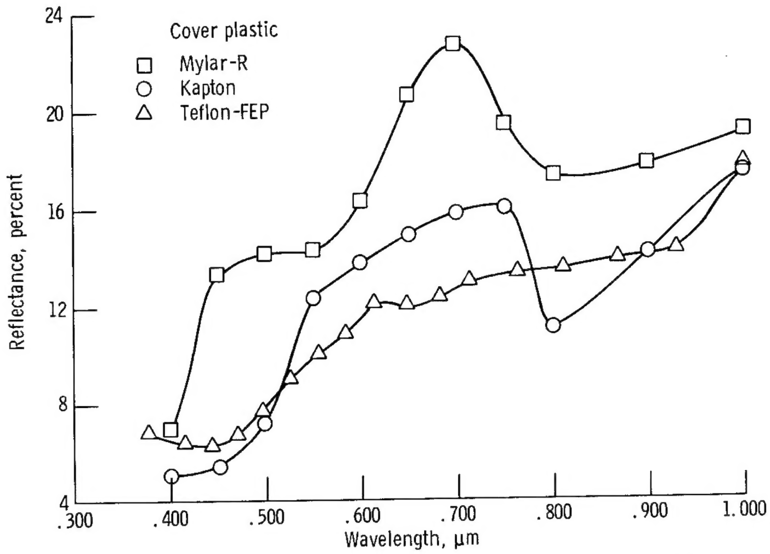

Figure 3. - Reflectance of solar cells covered with Mylar-R, Teflon-FEP, and Kapton.

Electron and Proton Bombardment Tests

A comparison of the effect of 1-MeV electrons on the transmission of Mylar-WD, Kapton, X101, PPT, and Teflon-FEP is shown in table IV. For fluences up to 1×10^{17} electrons per square centimeter, Kapton is unaffected. Mylar-WD loses 14 percent of its initial transmission after the same fluence. Teflon-FEP is unaffected by a fluence of 2×10^{16} electrons per square centimeter, the highest bombardment level attained. X101 and PPT are darkened by a fluence of 8×10^{15} electrons per square centimeter, and since their ultraviolet performance also was not good, further testing was discontinued. Included in the table are data on the effect of proton bombardment of Teflon-FEP. The film is unaffected by fluences up to 1×10^{14} protons per square centimeter of 800-keV protons. Protons of this energy will be stopped completely by the film, as estimated by the method of Barkas and Berger (ref. 6). Curtin has shown (ref. 7) that for solar cells covered with Kapton, a fluence of 1×10^{14} protons per square centimeter of 800-keV protons results in a power loss of 4 percent. However, he also points out that there are annealing effects on the damage to the plastic. It is possible that if some damage had occurred to the Teflon-FEP in the bombardment, it could have annealed out by the time the transmission was measured at this laboratory several days later. However, if this were so, the transmission loss was slight since noticeable discoloration was not evident when the samples were removed from the facility (private communication from J. Hirschfeld, NASA Goddard Space Flight Center). Thus, it appears that Teflon-FEP will be as good as Kapton in resistance to protons of this energy. The equivalent

TABLE IV. - EFFECT OF ELECTRONS AND PROTONS

ON FILM TRANSMISSION

Plastic	Fluence of 1-MeV electrons, electrons/cm^2					
	0	1×10^{15}	8×10^{15}	1×10^{16}	2×10^{16}	1×10^{17}
	Relative transmission[a], percent					
Mylar-WD	95	87	--	82	---	--
Kapton	76	76	--	76	---	76
X101 (sample 1)	91	---	85	---	---	--
PPT	91	---	89	---	---	--
Teflon-FEP	109	109	--	109	109	--

Plastic	Fluence of 800-keV protons, protons/cm^2			
	0	1×10^{12}	1×10^{13}	1×10^{14}
	Relative transmission[a], percent			
Teflon-FEP	109	109	109	109

[a]All transmission data are expressed as percentage of initial transmission of Mylar-R.

time in the Van Allen belt at an altitude of approximately 2000 miles for fluences of 10^{14} protons and 10^{16} electrons of these energies is approximately 1 year (ref. 8).

SUMMARY OF RESULTS

Plastic films, suitable as covers for thin-film cadmium sulfide solar cells, were irradiated by ultraviolet light in vacuum. The intensity of the source was equivalent to 7.5 suns for wavelengths less than 0.300 micrometer. The films were also irradiated by electrons and one of the films, Teflon-FEP, by protons. The following results were obtained:

1. Teflon-FEP showed very good resistance to degradation by ultraviolet light and retained its superior transmission properties in the wavelength range 0.350 to 1.200 micrometers after more than 16 000 equivalent solar hours (ESH). It also showed no transmission change after bombardment by 1-MeV electrons at fluences up to 2×10^{16} electrons per square centimeter and 800-keV protons at fluences up to 1×10^{14} protons per square centimeter. The results of these tests indicated that Teflon-FEP is a good prospect for use as a solar cell cover material. Its applicability to solar cell manufacture, however, will depend on mechanical and processing properties not treated herein.

2. Kapton degraded slowly and continuously under the test conditions. Compared with Mylar-R, the transmission of Kapton went from 75 to 65 percent after more than 20 000 ESH (or 2 years at 1 AU). Kapton was unaffected by 1-MeV electrons at fluences up to 1×10^{17} electrons per square centimeter.

3. Parylene degraded under ultraviolet irradiation, losing 16 percent of its transmission in less than 1000 ESH. Parylene continued to degrade, although more slowly, and after 20 000 ESH was still more transparent than Kapton.

4. Mylar-WD degraded rapidly under ultraviolet light. It became brittle and hard to handle. The film also degraded under bombardment by 1-MeV electrons up to fluences of 1×10^{17} electrons per square centimeter.

5. X101 degraded in ultraviolet light similarly to Mylar-WD, but it was only slightly affected by 8×10^{15} electrons per square centimeter of 1-MeV energy.

6. PPT behaved similarly to X101.

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National Aeronautics and Space Administration,
Cleveland, Ohio, August 21, 1969,
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